HIGH DENSITY HGCDTE AVALANCHE PHOTODIODE ARRAY PERFORMANCE [1]

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ABSTRACT

Recent advances in Infrared materials and device design have been applied to developing a new class of high sensitivity II-VI Avalanche Photodiodes (APDs) for eyesafe applications. These devices utilize $Hg_{1-x}Cd_xTe$ and are designed using separate absorber and avalanche layers. Low excess noise at high gains is achieved by exploiting the natural resonance for hole avalanche multiplication in the gain region while high quantum efficiency is obtained by separately optimizing the thickness and field in the absorbing regions. The excellent k-value (ratio of electron to hole ionization coefficient) 0.1 achieved for $Hg_{1-x}Cd_xTe$ is particularly advantageous in the development of APD arrays for 3D LADAR imaging applications. HCT APDs show promise for laser range finders with increased range and 3D/flash imaging arrays. Eyesafe APDs fabricated utilizing MBE with a low defect growth process have demonstrated for the first time NEPs in the low nW or sub-nW range for 50 micron diodes. High Density (32x2, 50 µm centers) LPE APD arrays fabricated under the CELRAP program and peaked at 1.6µm have demonstrated low NEP and dark current and high operability. A large majority of APDs statistically sampled at the wafer level operate with a gain of 10. Measurements on one of the better arrays show that (excluding 5 damaged diodes) 26/27 (96%) meets the performance requirement of 5nW. Eighty six percent fall in the range from <0.8nW – 2nW. Dark currents normalized to unity gain at 296K are <8nA. LPE APDs and arrays with approximately 2 µm spectral cutoff have also been built. APD operation and gains in excess of 10 have been achieved for 100 micron and 200 micron diodes. Preliminary measurements on 100 micron APDs show dark currents at 300K in the low microamps at a gain of 10 and NEPs in the 30 – 40 nW range.

1.0 INTRODUCTION

The emergence of small footprint, high power lasers in the eye-safe regime (1.55 µm) enable compact systems for Laser Ranging and Target Identification. Common systems determine range by emitting a series of laser pulses typically ~ 10 ns in width with a rise time of ~ 2 ns. The laser return is detected and the time of arrival accurately determined by a counter. To accurately determine the target range at moderate laser power, the detector-amplifier combination must provide high sensitivity at high speed.

For 3D imaging LADAR systems designed to detect targets in the 2–10 km, medium power eyesafe lasers ~20-50 mJ consistent with laser designators may be used with high sensitivity APD arrays. Range accuracy requirements are typically 0.2 meter or less, corresponding to 1-2 ns or better temporal accuracy. At these ranges, the APDs must detect laser return pulses of the order of 100 photons with good S/N to achieve the required temporal accuracy. Corresponding detector NEPs must be of the order of 1 nW.

2.0 SYSTEMS BENEFITS OF HgCdTe

Detection of the high-speed return is aided by amplification of the signal in the detector. Achieving this gain with low noise is critical for such systems. Almost a factor of 2-improvement in range is achievable by utilizing HgCdTe APDs at a gain of 30 with low k-values ~ 0.1 versus InGaAs APDs with k~ 0.5 and a gain of 10. At gains above 10, InGaAs APDs suffer from excess noise.

3.0 EYESAFE HgCdTe MBE APD PERFORMANCE

HgCdTe APDs designed for optimum performance at 1.55 µm were fabricated using the HgCdTe Molecular Beam Epitaxy facility at HRL. The growth process was carefully adjusted to achieve low levels of native defects. As received epitaxial wafers were processed through mesa formation, passivation and metalization to yield both single element APDs and small 5 x 5 arrays.

A photomicrograph of a portion of the wafer, Figure 1, shows representative processed APDs of various sizes with and without guards. A 5 x 5 test array is illustrated in Figure 2. Five wafers were characterized using the dedicated APD test facility at Raytheon IR Center of Excellence in Goleta. Measurements at probe included: DC parametric data, pulse response, and noise performance. Responsivity and gain measurements in the paper were made utilizing a 30 ns laser pulse at 1.55 µm. An effective noise bandwidth of 35 MHz was utilized in the calculations. Data from across wafer 1616 for better 50-micron diodes (measured at a gain of 10) show NEPs in the low nW or sub nW range, with the best value measured to 8.4e-11 w. Total dark current for these diodes at a gain of 10 were measured to be as low as 2.6 nA, equivalent to sub-nanoamp dark current at unity gain. Figure 3 illustrates a NEP map for a 5 x 5 test array. Except for the two damaged diodes all APDs are operable with a gain of 10. Eighteen out of twenty three diodes exhibit NEPs less than 1.5nW at a gain of 10.

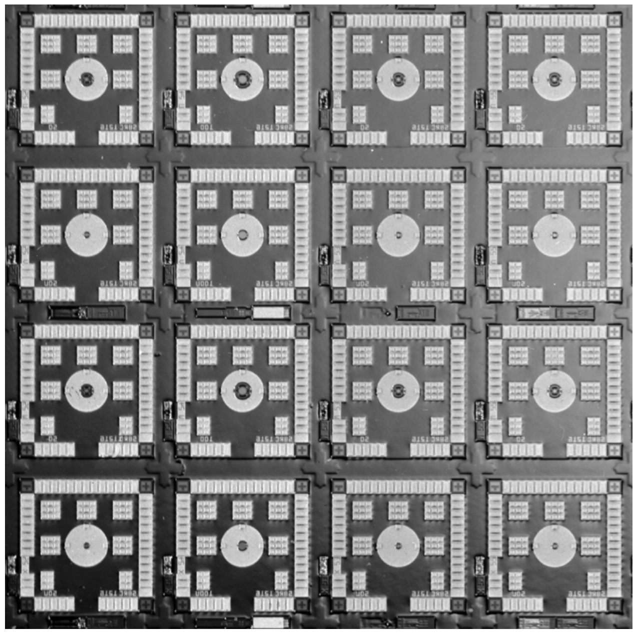

Figure 1. Photomicrograph of HgCdTe APDs from Portion of MBE Grown Wafer 1616

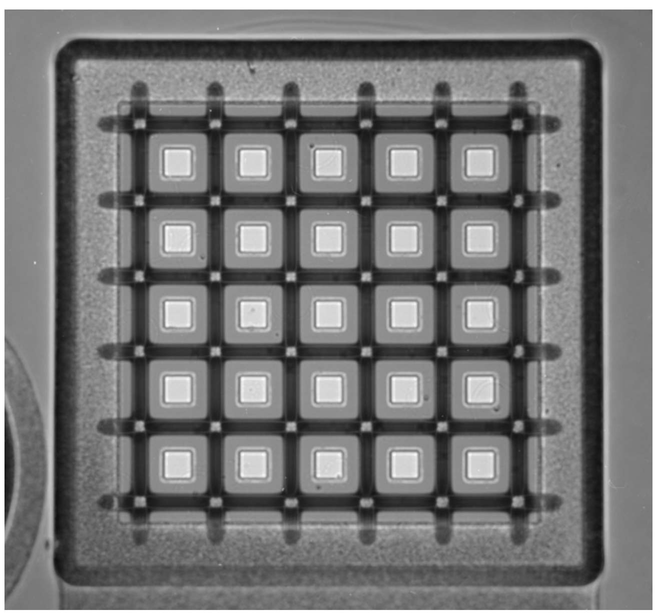

Figure 2. Photomicrograph of 5 x 5 Test Array of 50 Micron MBE APDs

Bold NEP @ QExG~10

A	A1	A2	A3	A4	A5
NEP(W)	**8.26E-10**	**1.22E-09**	**5.94E-10**	**1.17E-09**	**1.23E-09**
B	**B1**	**B2**	**B3**	**B4**	**B5**
NEP(W)	**7.17E-10**	**7.52E-09**	**5.08E-08**	**1.26E-09**	**1.26E-09**
C	**C1**	**C2**	**C3**	**C4**	**C5**
NEP(W)	**5.14E-10**	**9.79E-10**	damaged	**5.90E-10**	**3.94E-08**
D	**D1**	**D2**	**D3**	**D4**	**D5**
NEP(W)	**1.12E-09**	**8.05E-10**	**1.97E-09**	**5.44E-10**	**6.66E-10**
E	**E1**	**E2**	**E3**	**E4**	**E5**
NEP(W)	**8.44E-09**	**8.46E-10**	damaged	**5.19E-10**	**4.17E-08**

Figure 3. NEP Map of a 5 x 5 Test Array of MBE HgCdTe 50 Micron APDs

4.0 Eyesafe HGCDTE LPE APD Arrays & Performance

Eyesafe HgCdTe APDs were fabricated utilizing Liquid Phase Epitaxy at RIRCOE, Goleta. Diodes were optimized for eyesafe operation tuning the spectral cutoff of the absorber to peak at slightly over 1.6 microns. Spectral characteristics of a processed 100 micron x 100 micron diode are shown in figure 4. Quantum efficiency of approximately 80% was measured with no anti-reflection coating. Thirty-two element arrays were fabricated for the CELRAP program utilizing this LPE design. Arrays were fabricated on 200-micron centers (for obstacle avoidance) and 50-micron centers (for target profiling applications). Figure 5 illustrates several versions of arrays fabricated on 50 microns centers including both 50-micron x 50 micron and 50 micron x 100-micron geometries.

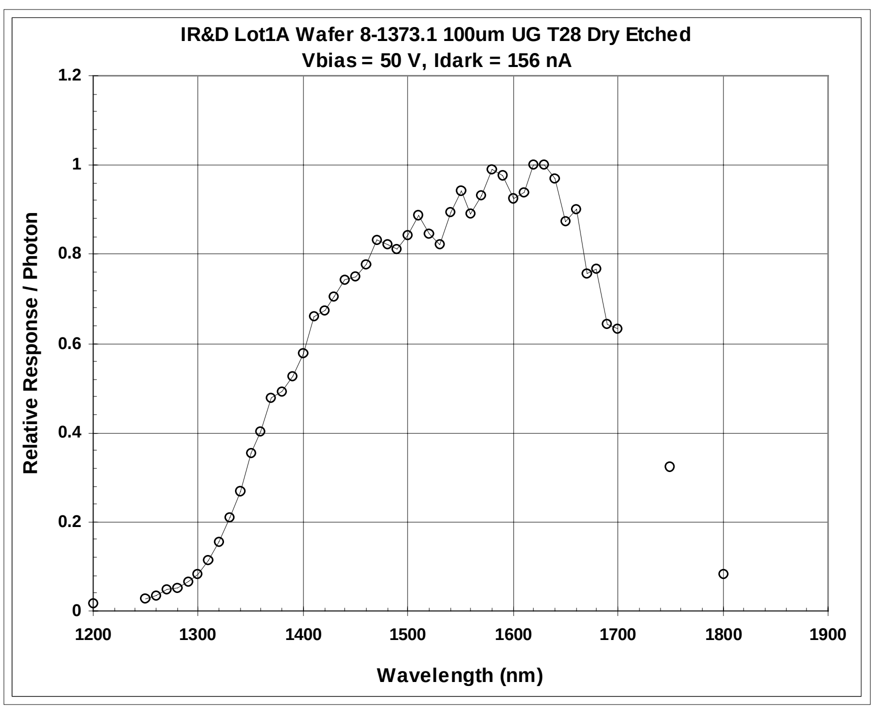

Figure 4. Spectral Charaacteristics of LPE HgCdTe APDs Fabricated for the CELRAP Program
The diode design has been optimized to peak at 1.6 microns. QE is approximately 80% with no ARC.

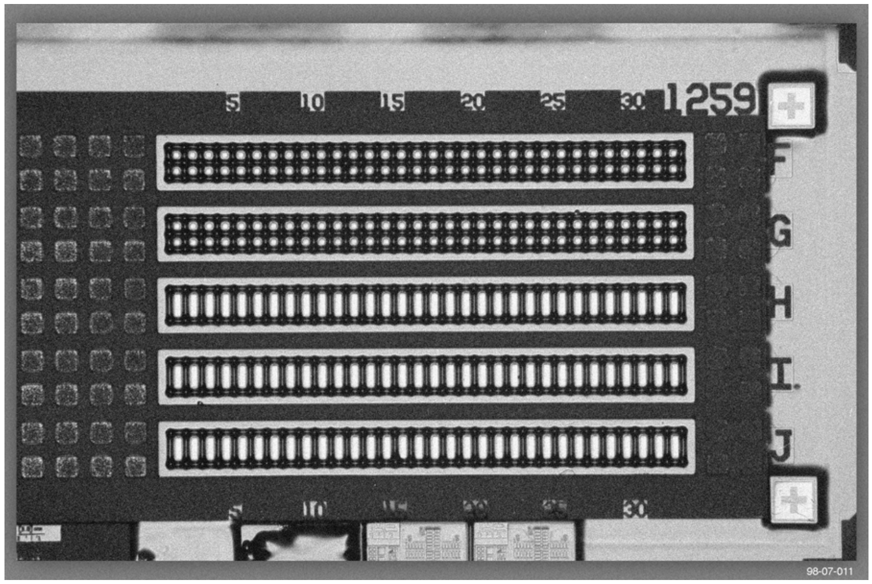

Figure 5. LPE HgCdTe APD Arrays for Target Profiling on 50 μm Centers. *The upper two arrays are a 32 × 2 square configuration, while the bottom three arrays feature rectangular 50 μm × 100 μm. Both geometries enable efficient capture of the return laser beam.*

Figure 6 shows a close-up of the 32 x 2 configuration delineated using Reactive Ion Etching technology. Gaps between diodes of less than 5 microns have been achieved.

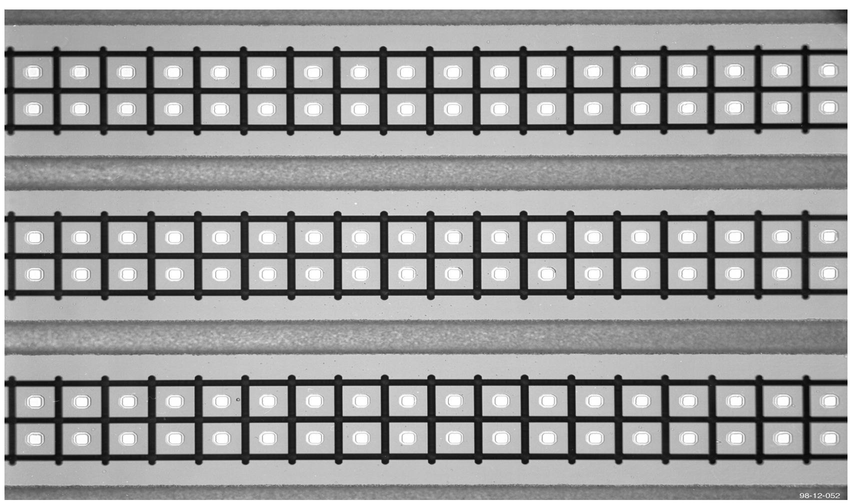

Figure 6. Photomicrograph of RIE Etched 32 × 1 Arrays of 50 μm square HgCdTe LPE APDs. *Only a small gap ≤5μm is seen between the mesas separating the individual APDs.*

Array characteristics were statistically determined by sampling 6 out of 32 diodes on each of four wafers. Parameters extracted at the wafer level included: dark current, gain, noise equivalent power (NEP) and bandwidth. The vast majority of the approximately 300 diodes measured operated as APDs with a gain of 10. NEPs of arrays fabricated on four wafers show typical values in the low nW range. A complete spatial map of one of the better 32 x 1 arrays is shown in Figure 7. Low NEP values, typically <5nW, is seen across the whole of the array. Because of difficulty in contacting the small 50-micron mesas, 5 APDs at the tail end (right side) of the array were damaged during tests. Alternate diodes from the upper array are substituted to assess the spatial map. Discounting the damaged diodes 26/27 (96%) of the diodes met the operational requirement and 86% of the diodes exhibited NEPs ranging from <0.8nW to 2nW.

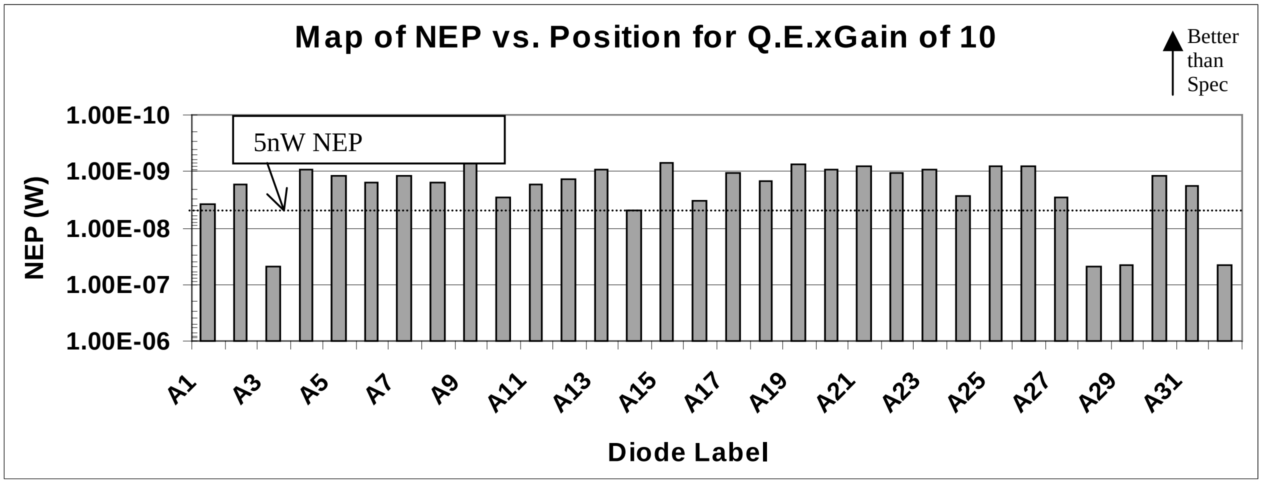

Figure 7. Map of NEP vs Position for Representative 32 x 1 HgCdTe LPE APD Array. *The dashed line represents an operational cutoff NEP of 5nW at a QE gain of 10. All diodes were fully operational. The diodes at the right side of the array were damaged during probing The higher NEPs observed on diodes 3, 29, 30 and 32 corresponded to increased leakage current at full gain. Discounting the damaged diodes 26/27 (96%) of the diodes met the operational requirement and 86% of the diodes exhibited NEPs in the <1nW – 2nW range.*

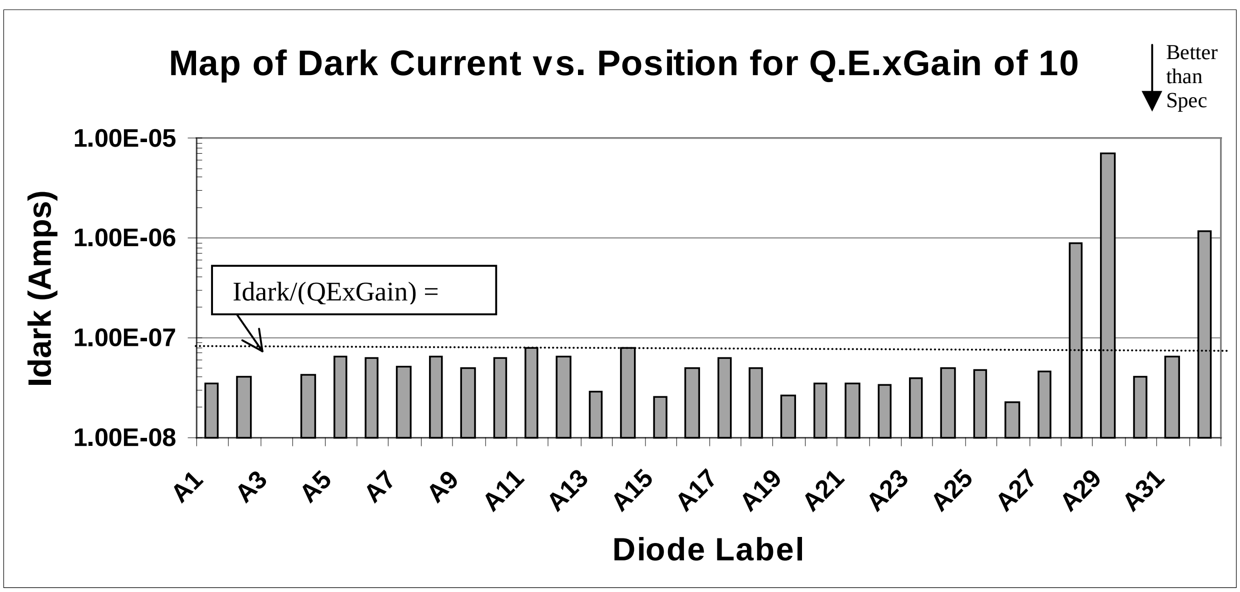

Figure 8. Total Dark Current (at QE x Gain = 10) vs Position for 32 x 1 HgCdTe LPE APD Array. *Diode spacing is 50 micron, Temperature is ~ 300K. Five diodes on the right were damaged during probe test. The dashed line corresponds to a normalized dark current Idark/(QE x Gain) = 8nA.*

5.0 PRELIMINARY DATA ON 2 MICRON HgCdTe LPE APDs

A number of LADAR applications including: wind velocity measurements, wind shear detection, and multispectral LADAR target discrimination benefit from development of an APD with 2 micron laser detection capability. Single HgCdTe APDs and arrays have been fabricated utilizing a Separate Absorption and Multiplication (SAM) design. Spectral characteristics of a typical diode is shown in Figure 9. Table 1 summarizes measured parameters from 100 micron x 100 micron APDs in a 32-element array. All measurements were performed at 296K.

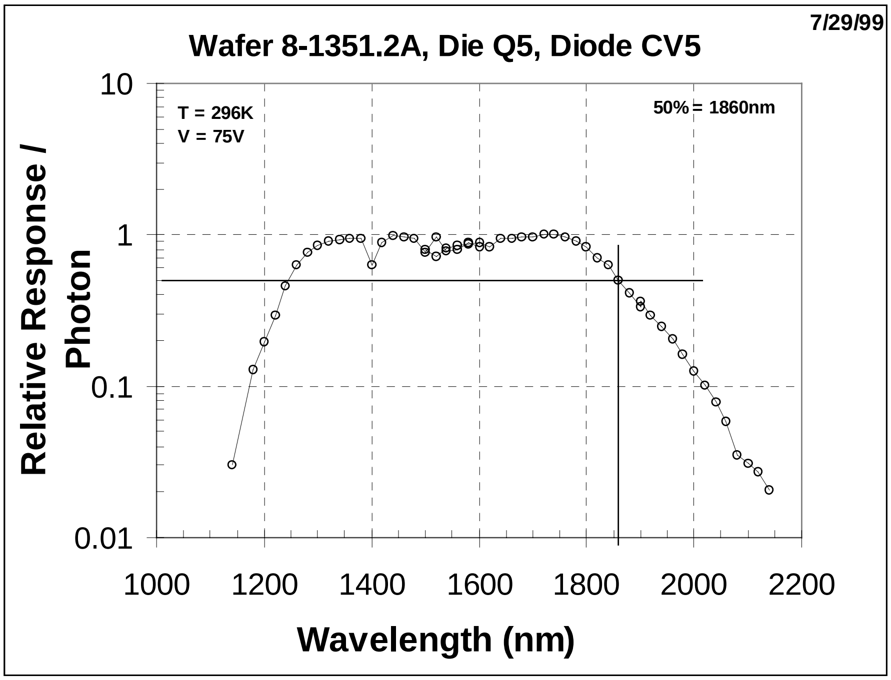

Figure 9. Spectral Characteristics of a 2-Micron HgCdTe APD Fabricated using Liquid Phase Epitaxy. *Diode size is in excess of 200-micron diameter. Measurement is taken at 300K. Nominal gain is 10 at 75 volts. The spectral half-power wavelength is 1.86 μm.*

Table 1. Parameters of HgCdTe APD Array with 2 Micron Spectral Cutoff (T = 300K)

Wafer : 8-1351.1
Die : F10 Unity QE x Gain Signal : 2.57E-02 Volts
Assy : 75466 1550nm Focused Pulse Response
Temp : 296 K Diode Area : 8.50E-05

Diode	Bias	Signal	t_{rise}	Noise	Dark Current	QE x Gain	Id / QE x G	NEP
	(Volts)	(mV)	(nSec)	(mVrms)	(μA)		(μA)	W
A	83.4	253.6	10.16	59	13.9	9.868	1.41E-06	2.7E-08
B	66.2	240.4	9.375	123	14.4	9.354	1.54E-06	6E-08
C	72.5	252.8	9.57	138	20.3	9.837	2.06E-06	6.4E-08
D	68.8	254.9	9.77	156	22.1	9.918	2.23E-06	7.2E-08
E	83.1	258.5	10.55	43.5	22.9	10.058	2.28E-06	2E-08
F	82.7	248.1	9.77	134	22.9	9.654	2.37E-06	6.4E-08
G	73.9	258.1	10.16	143	23.5	10.043	2.34E-06	6.5E-08
H	66.5	246.4	9.38	107	23.8	9.588	2.48E-06	5.1E-08
I	71.3	251.1	10.35	150	26.2	9.770	2.68E-06	7E-08
J	82.9	250.3	10.35	117	27.9	9.739	2.86E-06	5.5E-08

6.0 FUTURE DIRECTIONS

Future activities in development of HgCdTe APDs and APD arrays for LADAR applications at Raytheon include: Further optimization of diode performance and yield, development of MBE HCT APDs for very large area imaging arrays, and the development of advanced APD readout integrated circuits.

7.0 SUMMARY AND CONCLUSIONS

HCT APDs show promise for laser range finders with increased range and 3D/flash imaging arrays. Exploitation of the natural resonance of HCT enables low k values <0.1 and, as a consequence, sensitivities 4× better than InGaAs, with a corresponding 2× increase in detection range. Eyesafe APDs fabricated utilizing Molecular Beam Epitaxy optimized absorber/gain regions have demonstrated NEPs in the low nW or sub-nW range for 50-micron diodes (utilizing measured response to a 30 nS pulse). High Density (32 element, 50 micron centers) eyesafe APD Arrays have been fabricated using Liquid Phase Epitaxial Growth for NVESD under the CELRAP program. Spectral peak is tuned for 1.6 microns. For a typical array all 32 diodes operate with a gain of 10. Meausrements on one of the better arrays show that (excluding 5 damaged diodes) 26/27 (96%) meets the performance requirement of 5nW. Eighty six percent fall in the range from <0.8nW – 2nW. Normalized dark currents at 296K are <8nA. We have extended the cutoff of LPE APDs to 2 microns using a SAM design. Individual diodes and 32 element linear arrays with approximately 2-micron cutoff have been fabricated. APD operation and gains in excess of 10 have been achieved for both 100 micron and 200 micron diodes. Preliminary data on 100 micron parts shows dark currents at 300K in the low microamps at a gain of 10. NEPs are in the 30 – 40 nW range. Future directions include further optimization of diode performance and yield, development of MBE HCT APDs for very large area imaging arrays. And the development of advanced APD readout integrated circuits.

8.0 ACKNOWLEDGMENTS

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